LA-UR-21-26032
Approved for public release; distribution is unlimited.

Title: A Review of the Beirut Ammonium Nitrate Explosion

Author(s): Dickson, Peter

Intended for: LANL training video

Issued: 2021-07-26 (rev.1)

Los Alamos NATIONAL LABORATORY

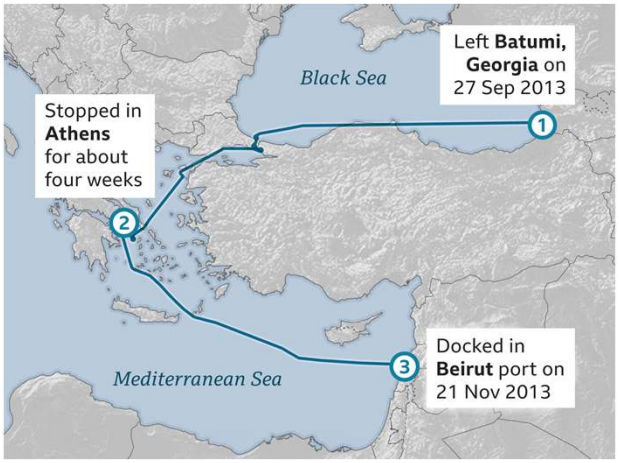
A Review of the Beirut Ammonium Nitrate Explosion

Peter Dickson

June 2021

The Ammonium Nitrate

In September 2013, the cargo ship MV Rhosus, an 87 m, single-deck cargo ship with two cargo holds totaling around 4000 m³, was chartered to transport 2750 metric tonnes of bagged (in 1000 kg sacks) explosives-grade ammonium nitrate from a Georgian fertilizer manufacturer (Rustavi Azot LLC) to an explosives manufacturer (Fábrica de Explosivos Moçambique) in Mozambique.



MV Rhosus
Built in 1986 by Tokuoka Zosen K.K. in Naruto, Japan.

How the AN ended up in Beirut

On November 21, 2013 the Rhosus docked in Beirut, Lebanon, to pick up an additional cargo of heavy equipment, apparently to fund its passage through the Suez Canal.

The heavy equipment was stacked on the cargo hold hatch covers, damaging them, and the Beirut Port Authority declared the ship unseaworthy in May 2014.

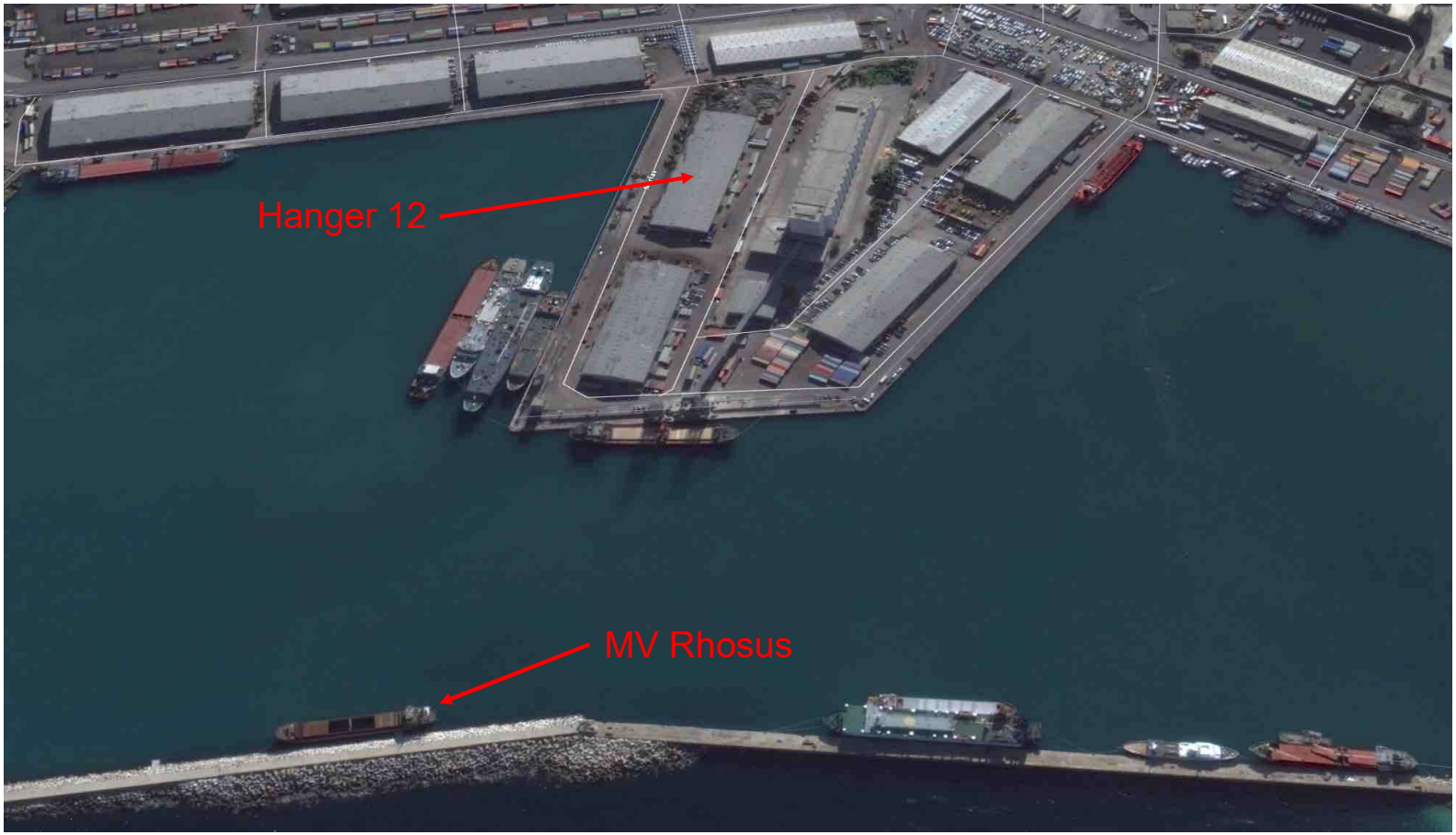
The ship's owner declared himself bankrupt, the chartering company abandoned the cargo, and the owner abandoned the ship.

On February 14, 2014, the Beirut Port Authority had impounded the ship and cargo, and in October 2014, as a result of a court order, the ammonium nitrate was unloaded and placed in Hanger 12.

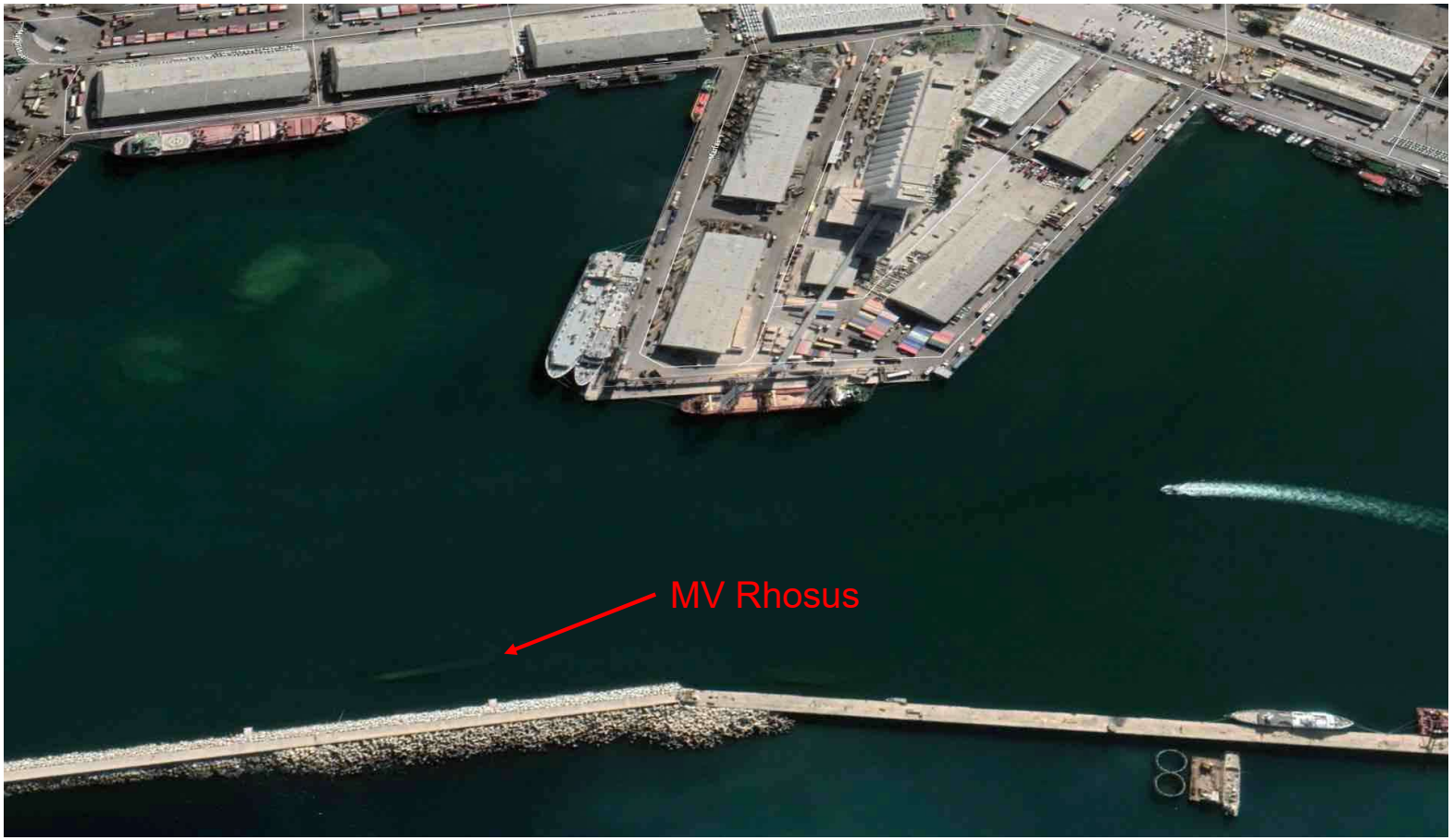
Bagged ammonium nitrate in the forward cargo hold of the MV Rhosus

May 2014 – MV Rhosus location (still loaded)

Late 2014 – moved to harbor wall after unloading



February 18 2018 – MV Rhosus takes on water and sinks



August 2020

Port location in Beirut

Inside Hanger 12

- Housekeeping was sub-optimal;
- The sacks of AN appear very randomly stacked, with no gaps as required by storage guidance;
- Bags are leaking, and show signs of contamination with unknown substances;
- Other materials that we would consider entirely incompatible with explosives storage were co-located including visible flammable wooden pallets and other goods.

Hanger 12 configuration in August 2020

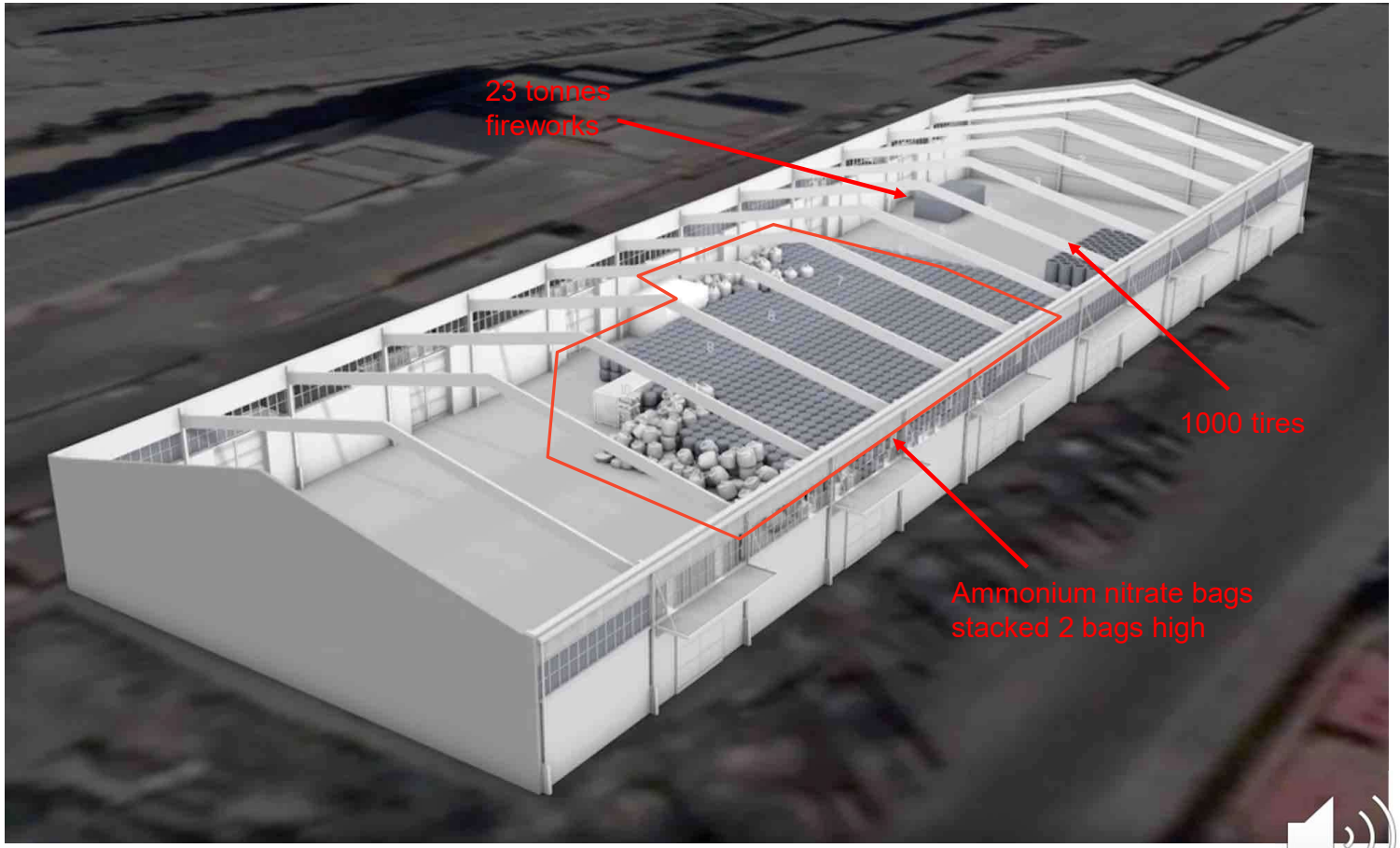
Hanger 12 loading as reconstructed by Forensic Architecture (UK) based on photos and videos.

Reports also indicate that the building also housed, in unknown locations:

- 50 tonnes ammonium phosphate
- 23 tonnes of fireworks
- 5 rolls of det cord
- 5 tonnes of tea and coffee
- 1000 tires

The danger presented by the ammonium nitrate was somewhat understood. Numerous requests were made by Lebanese Customs officials over the next few years to have the material removed, including noting that it had the potential to destroy the city.

No action was taken.



August 4, 2020

Shortly before 1800 on August 4, 2020, a fire started either in or adjacent to Hanger 12. The cause is disputed, but was probably welding operations to repair the hanger structure.

Lesson learned: welding should not be conducted in the presence of explosives

At 1755 a team of firefighters arrived to attack the fire.

The following video sequences start at 1757, taken from an apartment building approximately 1 km to the SE.

T – 00:9:36 (4/8/2020 17:57) Light-colored smoke of unknown origin

T – 00:06:15 Darker smoke appears – possibly involving the tires

T – 00:04:18 » Getting darker – definitely looks like rubber burning

T – 00:00:35 » First explosion involving fireworks, then detonation

Slow motion

Other views

1375 m

665 m

Nitrogen dioxide cloud

Before…

The day after…

- Total destruction out to around 500 m.
- Serious damage out to 1500 m.
- The blast caused a crater 125 m in diameter and 45 m deep, with seismic stations measuring 3.3 – 4.5 magnitude.

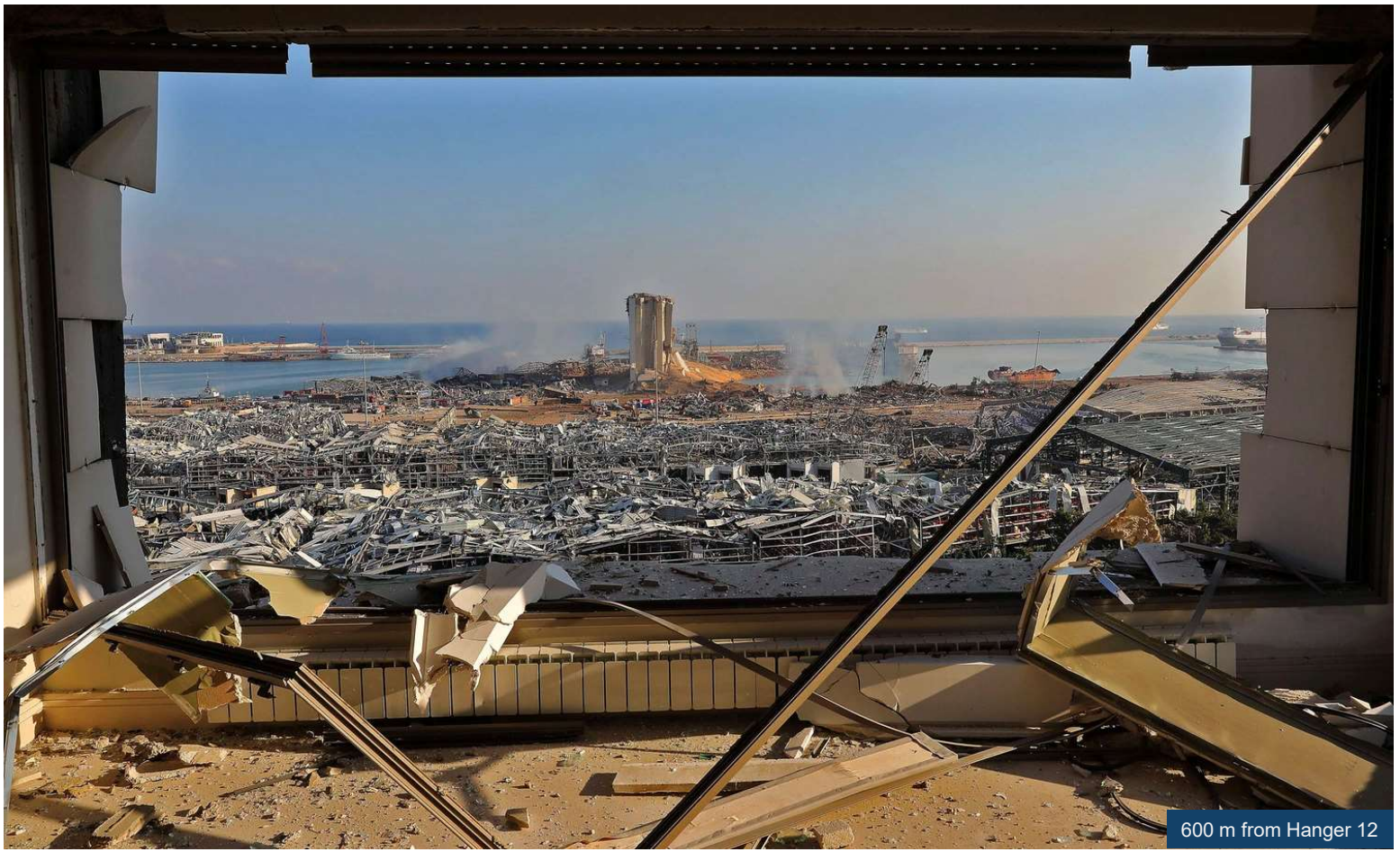
Photos

Photos

Photos

Oil tanker Amadeo II initially at 65 m thrown out of the water

Photos



600 m from Hanger 12

Photos

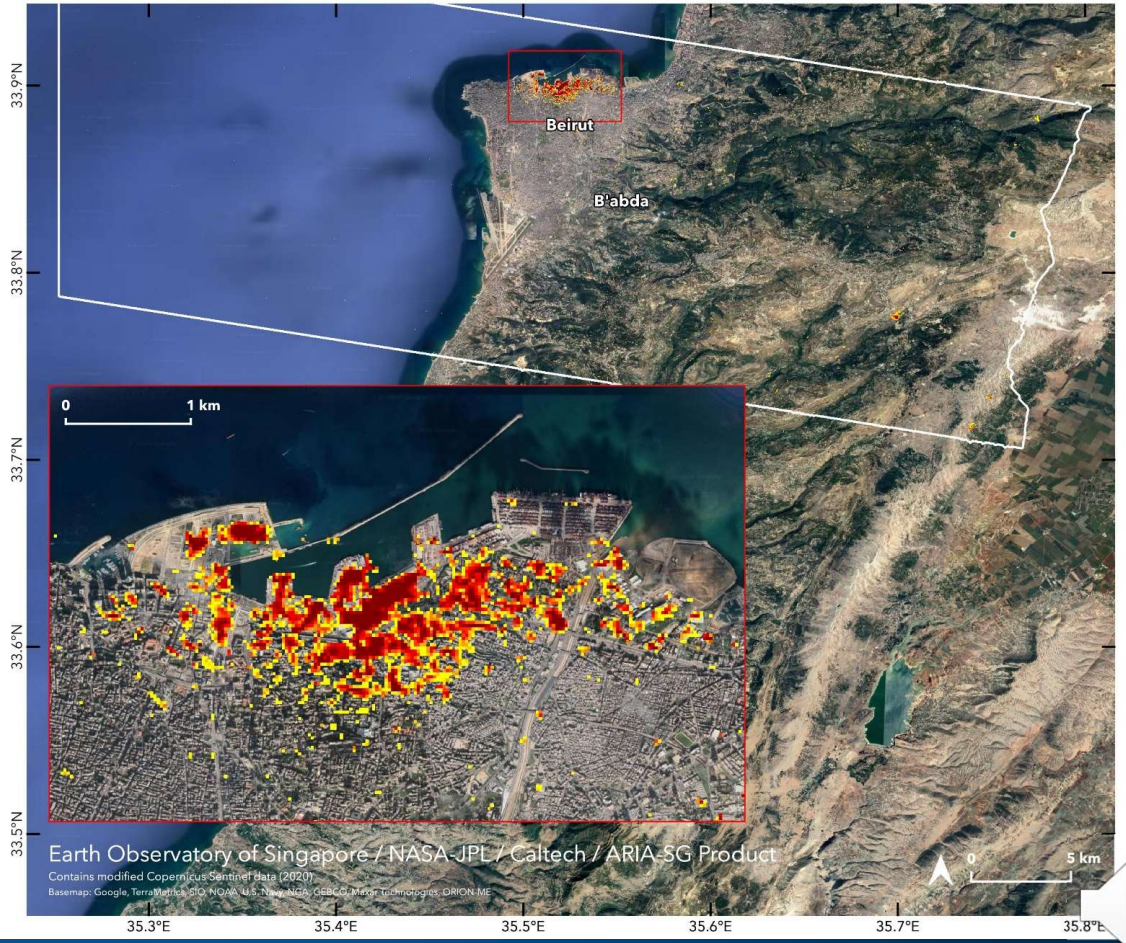
Collapsed buildings at 700 m

Damage map

Serious structural damage to buildings extended well over 1 km from the site. Buildings were damaged as far as 10 km out.

Over 200 people died and more than 6500 were injured.

The estimated cost is over $15B.



Yield estimates

Various methods can be applied to estimate the explosive yield in equivalent TNT mass:

- Fireball size
- Seismic effects
- Blast wave profile

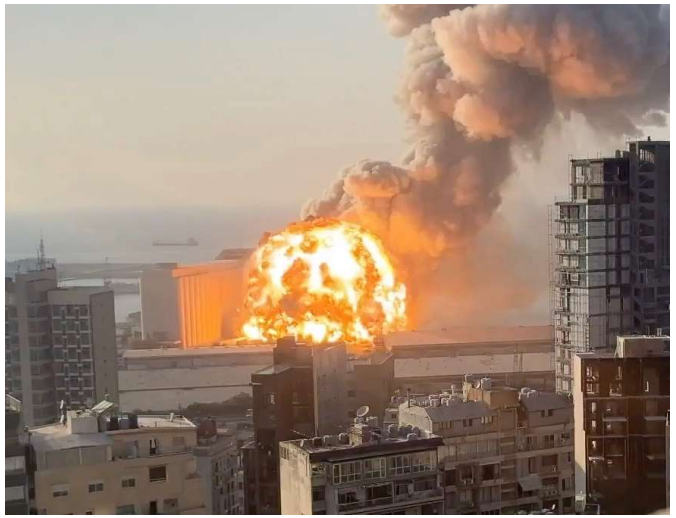
When the first videos surfaced that day I measured the fireball equivalent radius from individual video frames with structure size references, and used a relatively simple empirical relationship between fireball radius, *R*, and TNT equivalent yield, *W* :

$R = 0.925 \sqrt[3]{W}$, where *W* is in kg and *R* is in meters.

Due to the cubic dependency of *W* on *R* the uncertainty is fairly large.

The TNT equivalence of pure AN is in the range 0.3 - 0.4, so the 1.2 kt estimate is almost certainly too high.

1 kt would correspond to detonation of most of the 2750 tonnes in the building.



R ≈ 90 m
⇒ W = 0.9 kt

R ≈ 100 m
⇒ W = 1.2 kt

Other yield estimates

The Federal Institute for Geosciences and Natural Resources in Germany estimated between 0.5 and 1.1 kt based on seismic measurements.

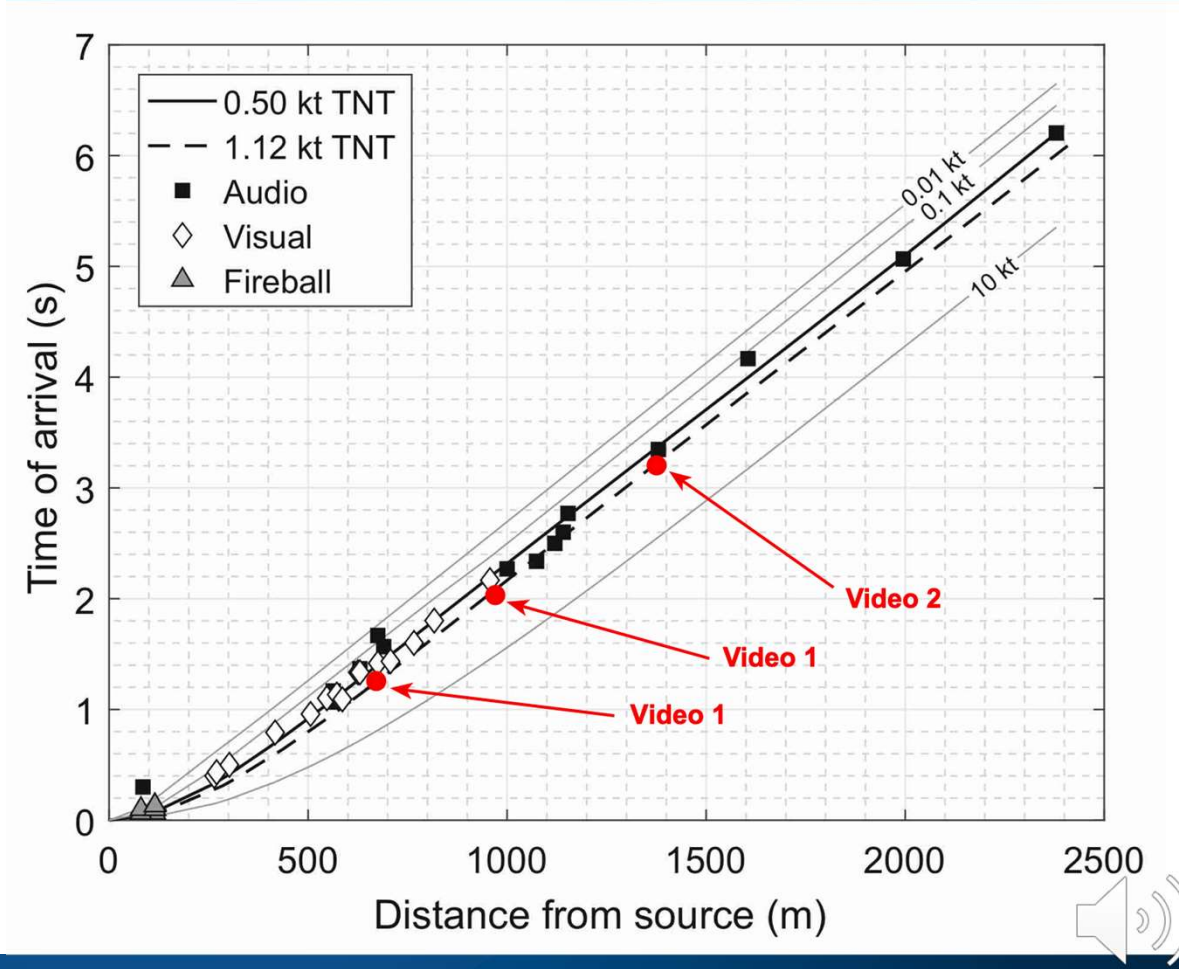
Rigby et al. from the Department of Civil and Structural Engineering, University of Sheffield measured the blast wave arrival times from 16 videos, and applied the Kingery & Bulmash approximation to get an estimate of 0.5 kt, with an upper bound of 1.12 kt.

0.5 kt would correspond to detonation of around 1500 tonnes of AN, or just over half the stored total.

The graph on the right shows the time of arrival of the blast wave plotted for the 16 video locations, with the authors finding the best fit to a curve for 0.5 kt. But note how sensitive this yield estimate method is to the time of arrival data.

I've added points for the measurements that I made for the videos shown earlier, all of which lie near the 1 kt yield curve. While I haven't checked every video that they used, they seem to have incorrectly measured either distance, TOA or both in the all the ones that I looked at.

It seems reasonable to conclude that the yield was in the 0.5 – 1 kt range, but I think that it was nearer 1 kt.



Pressure and sound level at video location

Using a value of 1 kt and calculating the *k* value gives *k* = 24, coincidentally exactly the Class 1 level of protection criterion.

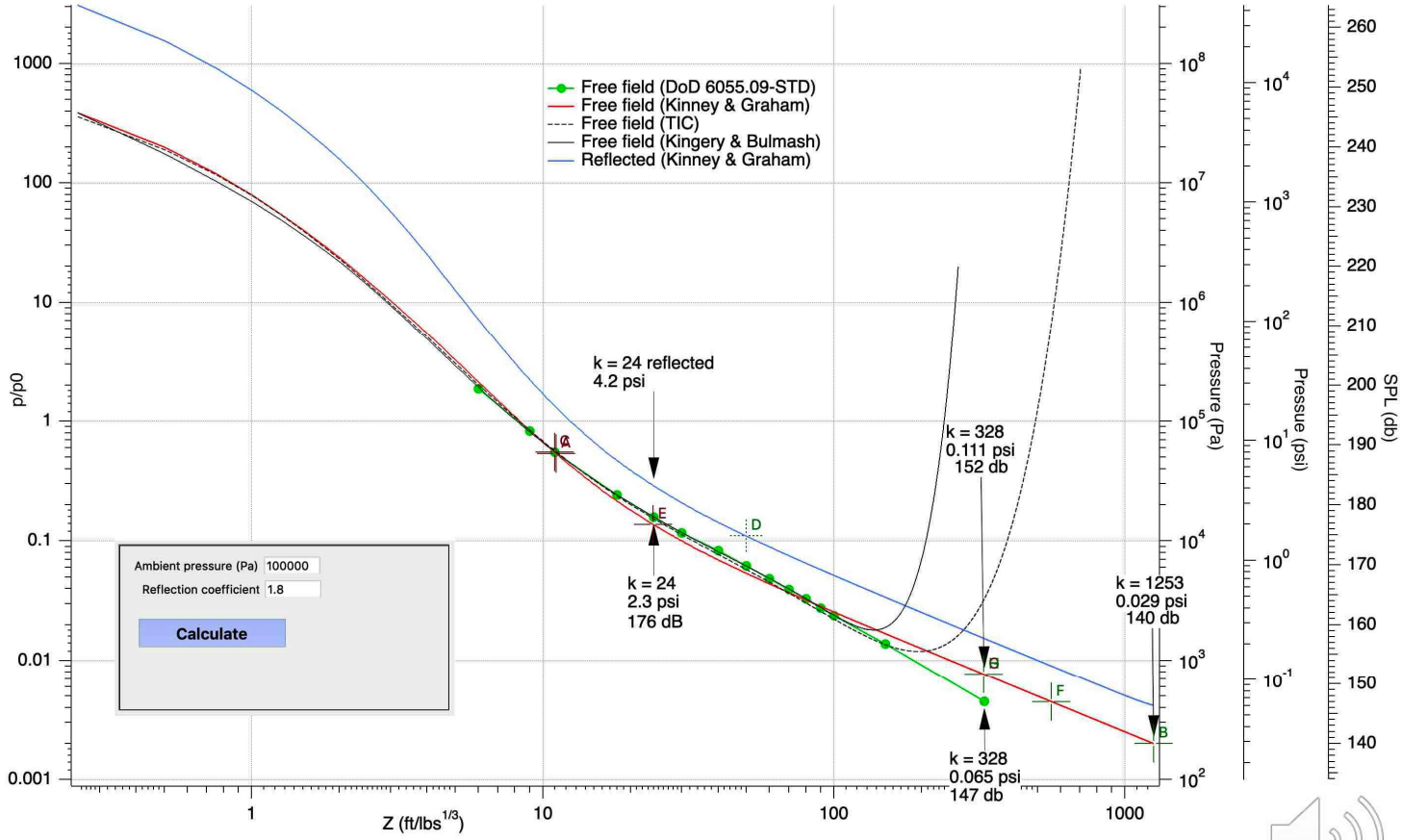
Using Kinney & Graham that gives a free-field blast overpressure of 2.3 psi and sound level of 176 dB at the video location. That's approximately half the 50% threshold pressure for human eardrum rupture

Equivalent to standing:

- 240 ft from a 1000 lb shot
- 110 ft from a 100 lb shot
- 50 ft from a 10 lb shot
- 24 ft from a 1 lb shot

Under DOE regulations the k328 outdoor firing hazard distance would be 8 miles.

The Rigby estimate of 0.5 kt equates to *k* = 30, with an overpressure of 1.5 psi and a sound level of 174 dB. The k328 distance would be 5 miles.



How did it detonate?

- There are really only two possibilities:
  - Shock input from an adjacent explosion or fast-moving projectile/fragment causing shock-to-detonation transition (SDT);
  - Deflagration-to-detonation transition (DDT) following thermal ignition.
- Pure ammonium nitrate with no added fuel is very oxygen rich and, while detonable, has a large critical diameter (> 2 ft) and is shock insensitive. It's a highly non-ideal, low-energy explosive. However, increased shock sensitivity and decreased critical diameter have been shown to occur in molten AN.
- While the AN in Hanger 12 was pure when shipped, it appears that it has significant contamination, at least on the surface, in later photos. Contamination by or addition of fuels increases the exothermicity of AN decomposition as well as increasing shock sensitivity, and adding water (5 – 10%) has also been shown to increase shock sensitivity while decreasing thermal decomposition rates.
- The inertial confinement needed for DDT to occur would likely mean that thermal explosion would have to occur deep in the stack of bags, but it does not appear that the fire was of long enough duration to heat that amount of material to ignition.

- CONCLUSION: we don't know enough to determine the mechanism.
  - The fireworks explosion may have led to subsequent fragment impact on hot AN.
  - The det cord may have been lit by the fireworks and exploded violently enough to throw fast fragments, even if it didn't detonate.
  - Something else, such as a sudden collapse of the stack, resulted in confinement that enabled a DDT process.

Texas City Explosion in 1947 – actually two explosions

EVENT

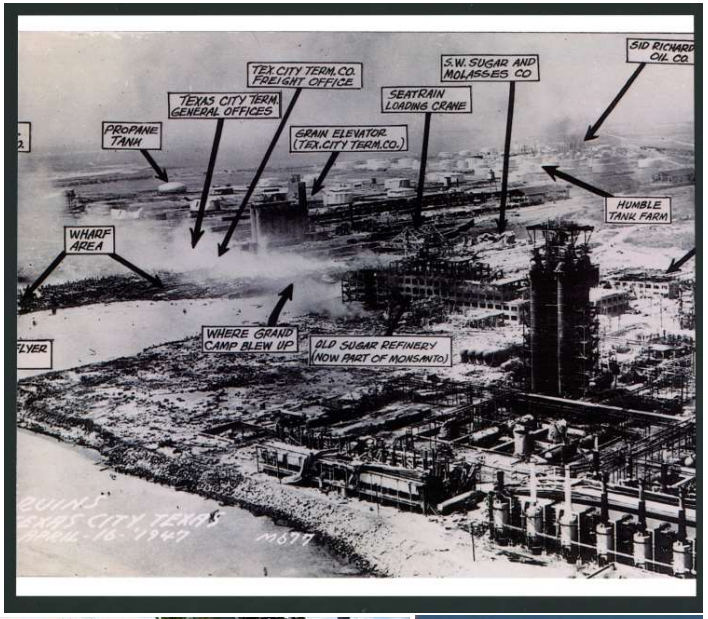
Fire started on the SS Grandcamp, a 130 m French cargo ship carrying ammunition, machinery, bales of twine and 2100 tonnes of fertilizer-grade, wax-coated ammonium nitrate. Attempts to extinguish, including steaming the cargo hold, failed. At 0912 on April 16, the ammonium nitrate detonated.

The explosion ignited cargo on the SS High Flyer, a 135 m cargo ship carrying 870 tonnes of ammonium nitrate around 800 ft from the Grandcamp. Attempts to extinguish that fire and tow the High Flyer out of port failed, and 15 hours later its ammonium nitrate detonated.

Texas City was largely destroyed by these explosions, with 581 killed and over 5000 injured. Windows were broken over 10 miles away.

CAUSES

- Fire starter unknown.
- Lack of understanding of the thermal response of ammonium nitrate.
- Misuse of steam fire suppression technique with AN.
- Failure to remove the Grandcamp from port when the fire was initially detected.



SS Grandcamp Anchor found 1.6 miles away

SS High Flyer propeller found 1 mile away

Brest, France 1947

EVENT

The Norwegian cargo ship *Ocean Liberty* was loaded with 3309 tonnes of wax-coated ammonium nitrate and other flammable products when it caught fire at 1230 July 28, 1947. The hold was sealed and pressurized steam was pumped in. This did not stop the fire and in fact exacerbated the situation.

The vessel was towed out of the harbor at 1400, and exploded at 1700, killing 29 and causing serious damage to the port of Brest.

CAUSES

- Fire starter unknown.
- Lack of understanding of the thermal response of ammonium nitrate.
- Misuse of steam fire suppression technique.
- Failure to tow the *Ocean Liberty* far enough from port.

Tianjin, China, August 2015

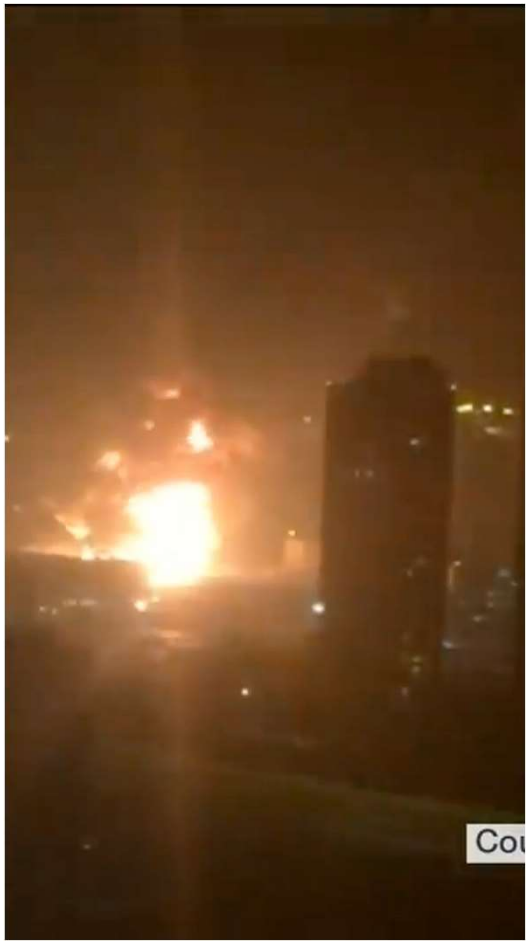
EVENT

Tianjin, China, August 2015. Nitrocellulose stored in a warehouse spontaneously ignited, causing the subsequent detonation, in two explosions, 34 seconds apart, of 800 tonnes of AN stored nearby.

The official casualty numbers were 173 killed and 797 injured. Over 300 structures were destroyed, and the blast produced a crater 100 m in diameter.

CAUSES

- Fire starter unknown.
- Incompatible materials stored in close proximity
- Lack of understanding of the thermal response of ammonium nitrate.



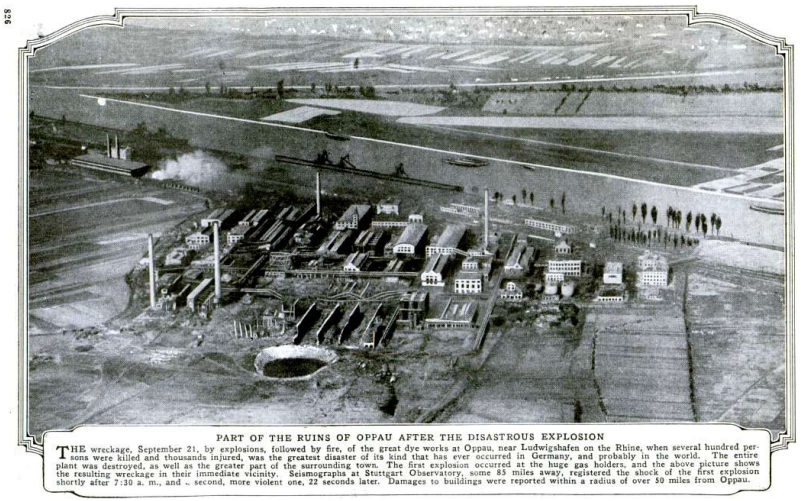
Oppau, Germany, September 1921

EVENT

4500 tonnes of a fertilizer mixture of 50:50 ammonium nitrate / ammonium sulphate was stored in 20 m tall silos. The hygroscopic AN caused the mixture to compact and harden, and it was common practice to disaggregate it with small charges of dynamite.

AT 0732 on September 21, that method led to detonation of an estimated 450 tonnes of nitrate-rich mixture.

561 people were killed, 80% of the buildings in Oppau were destroyed, and 6500 were left homeless.



PART OF THE RUINS OF OPPAU AFTER THE DISASTROUS EXPLOSION

THE wreckage, September 21, by explosions, followed by fire, of the great dye works at Oppau, near Ludwigshafen on the Rhine, when several hundred persons were killed and thousands injured, was the greatest disaster of its kind that has ever occurred in Germany, and probably in the world. The entire plant was destroyed, as well as the greater part of the surrounding town. The first explosion occurred at the huge gas holders, and the above picture shows the resulting wreckage in their immediate vicinity. Seismographs at Stuttgart Observatory, some 83 miles away, registered the shock of the first explosion shortly after 7:30 a. m., and a second, more violent one, 22 seconds later. Damages to buildings were reported within a radius of over 50 miles from Oppau.

CAUSES

- Use of dynamite to disaggregate an explosive mixture.
- Lack of understanding of the shock sensitivity of the ammonium nitrate / ammonium sulphate mixture.
- Lack of awareness of a similar, but smaller event at Kriewald, Germany, that had killed 19 people.

Conclusion

- **These kinds of catastrophic events are not going to happen at LANL; we don't store large enough quantities of explosives and storage magazines are sited to prevent damage to inhabited structures even in the event of mass detonation.**
- **However, they do illustrate the importance of a number aspects of our explosives safety program, since in each case it is easy to identify obvious deficiencies in the operations involved.**
  - Follow storage and handling guidelines and rules – most were put in place in response to accidents.
  - Understand the behavior of explosives, especially to abnormal stimuli. Simply knowing how they behave in design mode is inadequate.
  - Always conduct a robust hazard analysis with subject matter experts before any new explosives operation – don't just assume that it will be safe.
  - Once you have a procedure – follow it – but don't stop reviewing and learning from events.

- **QUESTIONS?**

Conclusion

- **These kinds of catastrophic events are not going to happen at LANL, if only because we don't store such large quantities of explosives.**
- **However, they do illustrate the importance of a number aspects of our explosives safety program, since in each case it is easy to identify obvious deficiencies in the operations involved.**
  - Follow storage and handling guidelines and rules – most were put in place in response to accidents.
  - Understand the behavior of explosives, especially to abnormal stimuli. Simply knowing how they behave in design mode is inadequate.
  - Always conduct a robust hazard analysis with subject matter experts before any new explosives operation – don't just assume that it will be safe.
  - Once you have a procedure – follow it – but don't stop reviewing and learning from events.

- **QUESTIONS?**